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Published in:
Proceedings of the 20th International EurOMA Conference

Publication date:
2013

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Citation (APA):
Herczeg, G., Akkerman, R., & Hauschild, M. Z. (2013). Supply chain coordination in industrial symbiosis. In *Proceedings of the 20th International EurOMA Conference* [SCM-19] European Operations Management Association.

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Supply chain coordination in industrial symbiosis

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Abstract
Industrial symbiosis (IS) is a form of supply chain cooperation in industrial networks in order to achieve collective benefits by leveraging each other's by-products and sharing services and utilities. This paper investigates the concept of IS from the perspective of supply chain coordination (SCC). For this purpose a theoretical framework is built based on SCC aspects, which is subsequently used to analyze a case study. We conclude that research is scant on operational issues and trade-offs as well as on challenges in terms of logistical integration. Also small-scale examples are barely studied or modeled.

Keywords: industrial symbiosis, supply chain management, sustainable development

Introduction
The term industrial ecosystem was first coined in 1989 introducing the idea of industries collaborating through exchanges of waste flows thereby utilizing resources better and reducing the impact on the environment (Frosch and Gallopoulos 1989). Industrial symbiosis (IS) is a feature of the industrial ecosystem thinking – establishing symbiotic relationships between separate industries in geographical proximity (Lowe, 1997).

From a supply chain perspective, IS is an industrial network including diverse and tight relationships between independent companies across supply chains (Miemczyk et al. 2012). Consequently, coordination of supply chain organization and operations is an important part of managing IS (Bansal and McKnight 2009). The supply chain aspects of IS are recognized by academics, but hardly any work on the topic has been published in journals related to operations and supply chain management.

The purpose of this paper is to study IS from a supply chain coordination (SCC) perspective and describe it using the terminology from this field and identify research gaps in the available literature. As part of this analysis, the paper presents a case study of the Kalundborg IS in Denmark, which is the most cited example of the phenomenon.

Research framework – supply chain coordination
A supply chain is a system of interdependent organizations manifesting the flow of physical goods and information (Chen and Paulraj 2004). The subject of SCC by

definition is not a single company but it is the supply chain structure, which can be a sequence of buyer-supplier dyads or an entire network of such chains (Miemczyk et al. 2012). Coordinating supply chains refers to the management of buyer-supplier relationships as well as their joint decision-making and actions towards mutually defined goals (Simatupang et al. 2002). Accordingly, Simatupang and co-workers divide the subjects of SCC into organizational and operational matters. The overall purpose of SCC is to manage inter-organizational challenges and to improve the operational performance of the entire supply chain by achieving coherency and improving complementarity between members (Simatupang et al. 2002). SCC encompasses long-term organizational design decisions as well as the short-term planning and control of operations (Fleischmann et al. 2008). Figure 1 depicts the context and aspects of SCC theory and is explained in more detail in the following sections.

Supply chain organization and operations

The network structure of a supply chain is determined by the interdependences between its organizations (Chen and Paulraj 2004). In terms of dependencies, supply chain members can share resources (e.g. raw materials and information) and facilities; and they also manifest the flow of goods (Kumar and van Dissel 1996). Typically, supply chains are described as a vertical chain where products flow downstream (forward) and upstream (reverse) (Vachon and Klassen 2006). In such flows along the supply chain, an organization can fill in the role of both supplier and buyer at the same time, and they define levels in the chain such as supplier, manufacturer, retailer and customer. Due to the complex network structure of supply chains (Miemeczyk et al. 2012) interactions can also happen in a horizontal manner (i.e. across different supply chains), typically in order to increase performance between supply chain levels (Cruijssen et al. 2007).

The main role of supply chain operations is the procurement, production, storage, transportation and consumption of goods through the levels of the supply chain (Fleischmann et al. 2008). The flow of goods is based on market transactions between supplier and buyer where products are exchanged typically for money. Additionally, information flows about central figures (e.g. sales data and demand forecasts) drive production and delivery; and determine inventories.

Decisions and performance measurement in supply chains

Supply chains are situated in an external context where they are subject to opportunities and constraints. Such drivers and barriers are raised for example by governance through legislation; and by technology through innovations and obsolescence. Supply chains are subject to – and impact on – the social environment as they employ workers and respond to human needs. Furthermore, during operations, supply chains interact with the natural environment consuming its resources (raw materials) and disposing waste and pollution to water, air and soil.

SCC essentially consists of decisions that are made over the planning horizon from strategic to operational levels (Fleischmann et al. 2008). Organizational design and decisions are responses to organizational challenges (Kumar and van Dissel 1996). In the long-term, the supply chain structure is designed, and strategic decisions are made regarding the selection of suppliers, buyers, materials, products, locations, technologies, partners and transportation modes (Fleischmann et al. 2008). In the short-term, operations are planned (e.g. production plan and material requirement, capacity allocation, sales and distribution plans) within the given supply chain design before being executed (Fleischmann et al. 2008). In supply chains, decisions and plans often

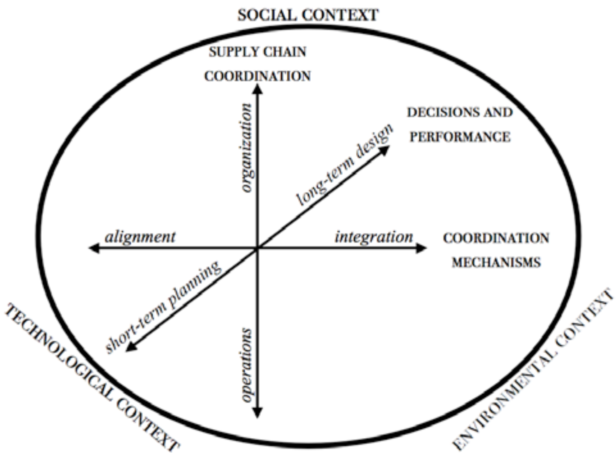

Figure 1 – Context and aspects of supply chain coordination theory

need to be made jointly by the involved supply chain members in order to combine goals and to achieve collective benefits (Arshinder et al. 2008).

Supply chain performance is usually measured in financial and operational terms (e.g. quality, delivery, flexibility, responsiveness) (Chen and Paulraj 2004). Operational performance eventually boils down to economic consequences and also affects the environmental impact (environmental performance) through the consumption of natural resources and production of waste and pollution.

Supply chain coordination mechanisms

Coordination mechanisms are ways for supply chain members to address organizational challenges and increase operational performance (Arshinder et al. 2008). Coordination mechanisms are characterized by their (1) complementarity (in order to manage organizational interdependences and improve supply chain performance); and (2) coherency (meant to integrate processes and reduce uncertainties, as well as to disseminate knowledge and information to achieve common understanding) (Simatupang et al. 2002).

In supply chains, integration is a means to ensure coherency. Integration can be technological or logistical (Vachon and Klassen 2007). Technological integration connects organizations through infrastructures and processes in the chain in order to be able to communicate and operate together. Therefore, technological integration involves strategic areas like the design and development of products, processes and managerial systems; furthermore, it is associated with the sharing of tacit knowledge (know-how) between the supply chain members (Vachon and Klassen 2007). A benefit of sharing explicit information (e.g. production plans and inventory levels) is that it reduces supply and demand uncertainty; consequently, logistical integration enhances the overall operational performance by improving responsiveness and flexibility and reducing stocks, waste disposal, and energy consumption (Chen and Paulraj 2004, Vachon and Klassen 2007). Consequently, integration is one way to improve competitiveness in supply chains.

Complementarity in supply chains is achieved through alignment and synchronization, and like integration it has both organizational and operational aspects (Simatupang et al. 2002). In general, organizations are either competing for maximizing benefits at the expense of the others or cooperating for collective benefits (Xu and Beamon 2006). In order to avoid and manage conflicts, organizations align their incentives based on contractual agreements and trust (Kumar and van Dissel 1996).

Furthermore, collective focus on synchronizing logistics (e.g. collaborative planning, forecasting and replenishment) allows to take into account and combine individual preferences and it has positive impact on overall supply chain performance; on the other hand, misaligned logistics undermines responsiveness and requires larger stocks (Chen and Paulraj 2004, Arshinder et al. 2008).

Supply chain coordination in industrial symbiosis

In an industrial ecosystem, waste is understood as a by-product that is a resource with some value (Zhu and Cote 2004). IS involves different independent industries in the exchange of by-products and residual resources, such as excess energy and water (Chertow 2000). Consequently, supply chain symbiosis in industrial networks is the manifestation of the flow of products, by-products, residual resources, and information.

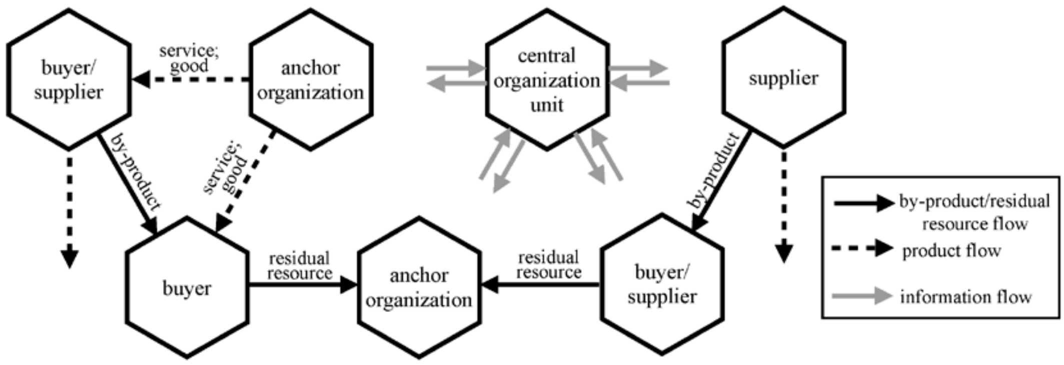

Figure 2 – Schematics of supply chain symbiosis in industrial networks

Organization and operations

In an industrial network, symbiosis may involve different types of organizational inter-dependencies across supply chain levels (see Figure 2). The structure of industrial symbiosis is built up from (1) dyads, which are pairs of companies exchanging by-products; (2) star networks, where a sole provider of a good or service is directly tied to its customers; and (3) fully connected networks, in which all members have direct ties to each other (Ashton 2008). Dyadic relationships often evolve between production plants from cement, fertilizer, oil, biofuel, paper, pharmaceutical, food and mineral industries and involve farmers, fisheries or breweries (Zhu and Cote 2004, Duflou et al. 2012). Furthermore, plants in IS usually settle around so called anchor organizations such as water suppliers, waste treatment facilities and energy providers (Chertow 2007). Star networks are typically organized around the anchor organization with several plants sharing its goods and services (Ashton 2008). Finally, IS often has a central organizational unit which is responsible for connecting the members, disseminating knowledge and ensuring central focus on sustainable development (Lowe 1997, Ashton 2008, Costa and Ferraro 2010).

In IS, demand for by-products is generated by the need of virgin resources, which they can successfully substitute. In other words, a by-product of one company is seen as feedstock for another company's production process (Bansal and McKnight 2009). In general, in IS suppliers and buyers conduct market transactions similar to vertical supply chains as well as share resources and services in a horizontal manner. Supplying by-products often requires additional conversion, transportation and substitution processes (Duflou et al. 2012). Operations in IS therefore involve the procurement, production, storage and transportation of by-products and other goods as well as the concurrent use of services. At the same time as it provides raw materials to buyers, the collaboration in an industrial symbiosis offers the suppliers of the goods a treatment of residual resources that would otherwise for them have been waste water or solid wastes (Chertow 2000). Plants in addition, also leverage excess energy (e.g. heat, steam) obtained from power plants and refineries (Chertow 2000). Figure 3 shows necessary operations and material flows related to by-product exchanges.

Intuitively, the generation and consumption of by-products relate to the main production process(es) in plants. Consequently, fluctuations in production affect the supply of and demand for by-products. However, by-product levels can be forecasted based on the production plans; and shortage and surplus can be dampened with stocks. Furthermore, the quality of by-products and residual resources often changes with the production batches, which complicates their further processing and use.

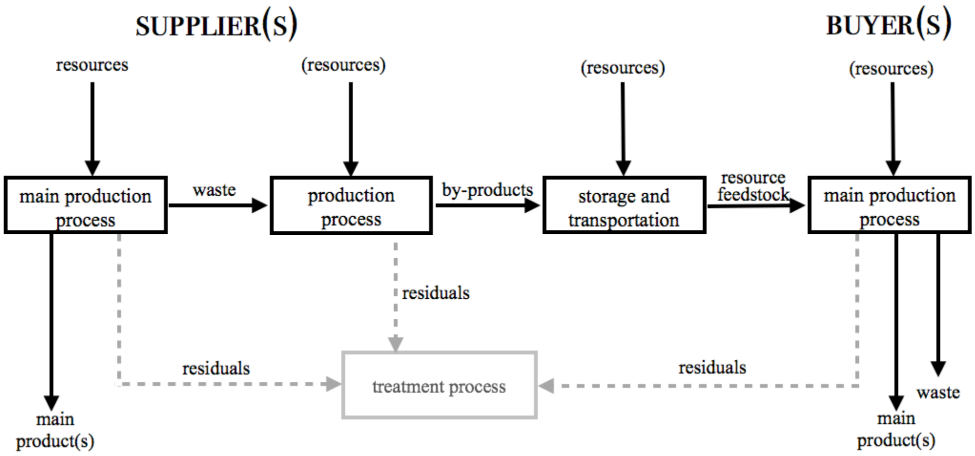

Figure 3 – Operations and material flows related to by-product exchange

Decisions and performance

Existing examples of IS have usually developed spontaneously between organizations from market opportunities providing competitive advantage, and carefully designed public attempts to IS are seldom successful (Desrochers 2004, Chertow 2007). In fact, investors might attribute high risk to by-product exchanges, due to the fact that an occurring failure of one company can endanger the entire network (Lowe 1997, Zhu and Cote 2004). On the other hand, Lowe (1997) argues that introducing redundancy in the relationships is useful to reduce the probability of failure of critical links. Indeed, being able to find alternative suppliers or customers for the by-product is key to IS resilience. Furthermore, long-term losses can also be reduced by increasing the diversity of material exchanges in the IS (Zhu and Cote 2004). Governmental interventions, business programs, scientific research and match-making consultancy can be successfully applied to expand the IS (Costa and Ferraro 2010), and mathematical programming can be used to determine optimal network design and to minimize cost and environmental impact (Cimren et al 2011).

Competitive advantage is attributed to the participation in IS due to the positive economic and environmental performance (Chertow and Lombardi 2005, Lee 2012, Duflou et al. 2012). Engaging in IS can create financial value for the participating companies by (1) reducing the cost of virgin resources for the buyer and generating extra profit for the supplier; (2) reducing disposal cost of the waste streams as these are taken over by partners in the network (Duflou et al. 2012). Besides generating revenue and reducing cost, recycling by-products also has potential environmental benefits which can be quantified by measuring changes in consumption of natural resources, and emission to air, soil and water (Chertow and Lombardi, 2005). However, Ashton (2011) finds that industrial symbiosis activities do not always meet the environmental performance expectations, particularly when the involved companies are focused only on their economic interests and the broader environmental implications are overlooked. Likewise, operations related to by-product and residual resource exchanges often incur additional investments, operational costs and environmental impacts (Duflou et al. 2012). Consequently, engaging in IS involves trade-offs in supply chain organization and operations.

Coordination mechanisms
Participating in IS requires technological integration between organizations, which involves communicating tacit knowledge, connecting industries through local infrastructure and combining production processes. Sharing tacit knowledge and collective learning has crucial importance for the long-term development of IS (Grant et al. 2010). Furthermore, building collaborative knowledge centers around IS with the purpose of monitoring and disseminating knowledge is found to be effective in the management of strategic development (e.g. Lowe 1997, Costa and Ferraro 2010). Connecting companies through local infrastructure is important in IS. For example, the transportation of excess heat, steam and waste water is realized with pipeline structures (Chertow 2007). On the other hand, engaging in IS reduces the dependency on the external infrastructure because waste streams are managed locally. Nevertheless, good railway, seaport and highway connections facilitate the development of IS. Production process integration is necessary in order to be able to utilize the by-product from another company (Zhu and Cote 2004). Being able to use a by-product possibly involves process adjustments because it might differ from the previously used virgin resource (Duflou et al 2012). Furthermore, logistical integration can have the same positive impact on the overall performance as in traditional supply chains. Consequently, engaging in IS requires technological integration on the organizational level and further logistical integration can be leveraged in order to improve the overall efficiency of operations.

In terms of alignment, industrial symbiosis emphasizes community, cooperation and coordination between the participating organizations (Bansal and McKnight 2009). Due to the symbiotic nature of the relationships it is crucial for the participating companies to understand that their existence within the symbiosis depends on each other (Baas and Boons 2004). Nevertheless, benefits do not always split fairly between the organizations (Chertow and Lombardi 2005), which can undermine long-term partnerships. Therefore, it is necessary that companies make contracts and agree on the division of investment costs and profit. It is also important that companies have common incentives and good communication in social and environmental terms (Baas and Boons 2004). Additionally, engagement in the local community gives trust and commitment to run businesses. On the other hand, due the complex network structure of the IS, synchronizing logistics is challenging, even though it could further improve operational performance.

Case study – Industrial symbiosis in Kalundborg, Denmark
Kalundborg is situated in the northern part of Zealand, Denmark. Its industrial park encompasses nine private and public enterprises including e.g. insulin and enzyme production, oil refining, energy production, cement production and sewage treatment (www.symbiosis.dk). Joint investments and cooperation between companies has been happening for more than forty years. Based on a series of interviews, the following sections study the IS based on our framework.

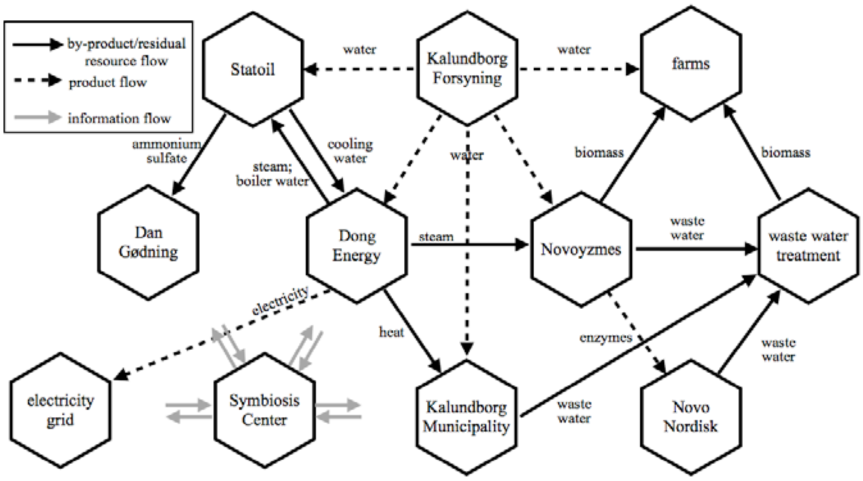

Figure 4 – Part of the supply chain network in the Kalundborg

Organization and operations

The Kalundborg Symbiosis (see Figure 4) is organized around central services (i.e. water supplier, waste water treatment facilities, power plant), which are concurrently utilized by the industries and the municipality of Kalundborg. The providers of these services have played the role of anchor organizations since the early years of the symbiosis. For example, reliable water supply is one of every plant's main concerns; therefore, Kalundborg Forsyning (the water supplier) has been contributing to the development of the industrial park since the 1970's. Similarly, the future of the symbiosis is determined by the anchor organizations. For instance, the energy policy of Dong Energy (the energy provider) shapes the strategy of the industries as well. Potential changes from coal-powered electricity to wind-powered electricity remove by-products like steam and residual water from the production; consequently, the other plants have to find alternative sources. Besides sharing utilities, production plants form dyadic relationships with each other building on products and by-product exchanges. For example, Novozymes supplies enzymes for companies next door; and provides the leftover biomass for the regional farmers who use it as fertilizer.

Refinement of waste streams to useable by-products may require introduction of additional operations. For example, Statoil applies a patented process to produce ammonium sulfate from sulfur that is left after oil refining; and Novozymes installed settling tanks on their site for generating biomass from the waste water left after enzyme production. Storage of some by-products happens on site either in tanks, silos or piles. For example, Statoil stores the ammonium sulfate granulates in tanks for several weeks before delivery. On the other hand, there are by-products and residual resources, like steam and boiler water, that cannot be stored due to their short shelf life. Transporting by-products and residual resources within and also outside the industrial park involves mainly pipelines and trucks. Pipelines are used to transport steam and residual water; while trucks are used to transport bulk materials such as biomass. In some cases in order to cover large distances vessels are used for transportation. For instance, Dan Gødning (a fertilizer producer) sends vessels from the other side of Denmark to procure ammonium sulfate from Statoil.

Decisions and performance

Engaging in by-product exchange is often associated with investments in new technologies; however, there are by-products, such as steam and heat that do not require further processing. By-product and residual resource supply and demand change over time as new opportunities are triggered by new technologies or as using by-products becomes obsolete or infeasible due to new legislations or new materials. For example, the waste water treating plant is currently establishing an algae farm in order to be able to produce high quality biomass based on a new technology. Novozymes not only provides biomass for farmers for free, but also takes care of the transportation and spreading, avoiding the fees for landfilling the biomass. On the other hand, Statoil had to stop delivering butane to the adjacent cardboard manufacturing plant when this buyer switched to natural gas because it was economically more feasible. In general, losing a by-product supplier or buyer would require an alternative; therefore, companies are necessarily seeking for new opportunities for leveraging synergies.

By-product exchanges in the Kalundborg Symbiosis are not different from traditional supplier-buyer relationships. This means that the relationships are normally based on business incentives in the first place and they are sustained as long as they create economic value. For example, Statoil stopped delivering liquid sulfur after transportation costs went up as their buyer moved their plant from Denmark to Finland. Utilizing by-products often gives competitive advantage because it reduces the total cost of production. For instance, farmers get biomass for free from Novozymes instead of paying for fertilizer. Similarly, buying steam from another production plant saves costs because it is cheaper than generating it on site. By-product and residual resource reuse obviously has environmental benefits as well. Reusing residual water for cooling purposes or for producing steam saves fresh water that is a scarce resource in the Kalundborg area. Furthermore, generating biomass from sludge that is left after waste water treatment is good for the environment because it substitutes chemical fertilizer with organic. In general, industries in Kalundborg have a strong environmental consciousness and they invest in innovations and green technologies around the industrial park. From a social perspective the Kalundborg Symbiosis plays a very important role in the development of the municipality as it attracts businesses to the area providing more local employment; furthermore, the investments in services and pipelines contribute to infrastructural improvements that are beneficial for the municipality as well.

Coordination mechanisms

Sharing experience and collective learning are institutionalized in the Symbiosis Center. Its aims are to draw attention to mutual problems and opportunities and align strategies of the companies; facilitate discussion between companies; and to collect and provide scientific data as well as disseminate knowledge inside and outside the symbiosis. The companies are represented in the board of Symbiosis Center where they meet at least annually to inform each other about their strategic orientations and make collective decisions regarding inter-organizational investments. Technological integration in physical terms is mainly realized with the pipeline systems transporting fresh and residual water, and steam throughout the industrial park and the municipality of Kalundborg. Sharing explicit information with each other and using common managerial systems is not typical in the Kalundborg Symbiosis. For example, knowing the waste water quality (i.e. organic matter quantity) is important for the treatment plant, but there is no such information available. Instead, the treatment plant relies on forecasts based on water samples. On the other hand, companies inform each other about the occurring shortages in by-product levels.

The long-term sustainability of the symbiosis requires common engagement and alignment from industries, which are continuously looking for new opportunities within the symbiotic network. In general, developments in Kalundborg are organized around four interest groups: (1) water recycling, (2) cascading excess energy like steam and heat, (3) exchanging by-products and (4) investing in test and demonstration facilities that promote green technologies, such as second generation biofuels and algae plantations. From a business perspective the relationships are based on long-term contractual agreements that specify the terms of delivery and costs. Companies in IS, however, are not only engaged in businesses, but they are also interested in the development of the municipality and protecting the local environment, which gives them another type of common incentive and also support from the local community. On the other hand, companies are not involved in synchronizing their logistics, but often have significant stocks of the by-products to decouple the individual processes.

Conclusion and future work

Generally speaking the concept of IS engages supply chains to form industrial networks levering by-product and residual resource exchanges for collective economic and environmental benefits. Although academic literature of IS recognizes its supply chain aspects, there is no comprehensive review of the phenomenon with clear supply chain perspective. This paper introduces an analytical framework based on the existing supply chain theory to analyze the concept of industrial symbiosis.

We find that organizational aspects are extensively studied in relation with IS. In fact, by-product exchange is not that different from traditional supplier-buyer relationships and the symbiosis is usually nurtured around services related to water and energy supply as well as waste treatment. IS is based on long-term alignment and integration between industries built on economic interests and supported by incentives related to the local environment and community. Companies in IS face strategic challenges as the feasibility of by-product exchanges changes over the time. On the other hand, we find that operational issues, such as trade-offs related to the production, storage and transportation of by-products are not studied in the academic literature. Furthermore, the effects of logistical integration and synchronization related to by-product exchanges are not investigated either. Therefore, we see ample opportunity for further research related to these aspects, as it would help further understand the operational side of IS, which would in turn enable improvements in the competitiveness and environmental performance of new and existing IS initiatives.

The introduced IS in Kalundborg is the classical example of the phenomenon and it represents supply chain aspects on the large scale. Nevertheless, in the future it would be interesting to investigate the IS concept on a smaller scale as well, where the symbiosis is manifested in dyadic relationships between two or three companies.

Acknowledgements

The authors would like to acknowledge the help from Lisbeth Randers (Symbiosis Institute), Lars Sørensen (Kalundborg Forsyning), Peter Holm Hansen (Novozymes) and Sven-Ole Toft (Statoil), who provided insight into the organization and operations of the Kalundborg Symbiosis.

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